PLASMA-FACING MATERIALS RESEARCH FOR FUSION REACTORS AT FOM RIJNHUIZEN*

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In next generation magnetic fusion devices such as ITER, plasma-facing materials are exposed to unprecedented high ion, power and neutron fluxes. Those extreme conditions cannot be recreated in current fusion devices from the tokamak type. The plasma-surface interaction is still an area of great uncertainty. At FOM Rijnhuizen, linear plasma generators are used to investigate plasma-material interactions under high hydrogen ion flux-densities up to 10^{25} $m^{-2}s^{-1}$ at low electron temperatures ($\leq$ 10 eV), similar to the conditions expected in the divertor of ITER. The incident ion fluxes result in power fluxes of > 10 MW/m^2. A new linear plasma device, MAGNUM-PSI, is expected to begin regular plasma operations in the middle of 2011. This device can operate in steady-state with the use of a 3 T super-conducting magnet, and a plasma column diameter projected to 100 mm. In addition, experimental conditions can be varied over a wide range, such as different target materials, plasma temperatures, beam diameters, particle fluxes, inclination angles of target, background pressures, magnetic fields, etc., making MAGNUM-PSI an excellent test bed for high heat flux components of future fusion reactors. Current research is performed on a smaller experiment, Pilot-PSI, which is limited to pulsed operation, a maximum magnetic field of 1.6 T and a narrow (~ 20 mm) column width. The research is primarily focused on carbon based materials and refractory metals. Erosion of materials, surface morphology changes as well as hydrogen implantation, diffusion and inventory in the materials are studied under fusion reactor conditions. The influence of neutron damages is studied by irradiation of the materials with high energy ions. A research programme addressing those before mentioned issues is presented.

Key words: ITER, fusion reactors, divertor.

1. INTRODUCTION

ITER, the next step device in a row of nuclear fusion reactors will experience unprecedented high particle fluxes. The main chamber with it's Beryllium plasma

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facing components will be exposed to a relatively hot edge plasma (T_e = 10-70 eV, n_e = 1 x 10^{19} m^{-3}) leading to heat fluxes of 0.4 - 5 MW/m^2. Those conditions can be achieved in current plasma wall interaction simulators. However, in the divertor of ITER the electron temperatures are much lower (T_e = 1 eV), leading to very high electron densities (n_e = 1 x 10^{21} m^{-3}) and unprecedented ion fluxes of 10^{24} $m^{-2}s^{-1}$ on the target. Those conditions cannot be achieved in current plasma generators. In addition transient heat loads as a result of so-called edge-localized modes (ELMs) threaten to limit the lifetime of the ITER divertor targets significantly. It is therefore that FOM Rijnhuizen is building a new generation plasma wall interaction simulator, Magnum-PSI, to assess exactly those ITER divertor conditions. A forerunner experiment, Pilot-PSI, is already in operation demonstrating the operational range of interest. The scientific programme has already started focusing on the most important ITER issues.

2. DESCRIPTION OF PLASMA GENERATORS

2.1. MAGNUM-PSI

Magnum-PSI [1] is a steady-state plasma generator able to produce a linear magnetic field of 3 T with its super-conducting magnet to simulate, within reasonable technical and financial limits, the ITER conditions (ion gyro-radius, confinement of large molecules and dust). The magnet system consists of five NbTi superconducting solenoids wound on one stainless steel former operating at 4.3 K [2, 3].

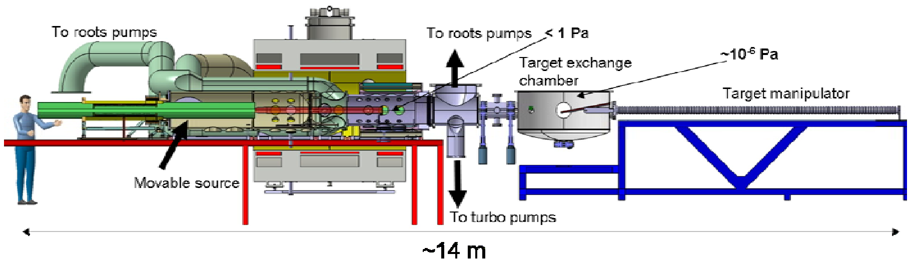

Fig. 1 – Magnum-PSI. After plasma exposure, the target is retracted by the manipulator to the target exchange and analysis chamber to perform detailed surface analysis.

The target can be tilted to the magnetic field to similar angles of those in ITER (~ 4 degrees). This requires ion fluxes of > 10^{25} $m^{-2}s^{-1}$. Those high ion fluxes at low electron temperatures are produced by a high pressure cascaded arc plasma source. The whole source system consists of the plasma source and a manipulator system allowing easy access to the plasma source for regular maintenance or source type exchanges. For the future operation of MAGNUM-PSI a pool of different sources from the type cascaded arc will be available specifically designed for particular applications (*e.g.* broad beam operation, pulsed high power source operation, high power narrow beam operation). The first plasma source will be a single channel 45 kW plasma source. As the next step a broad beam plasma source will be installed. This design is based on a multi-channel cascaded arc. The largest plasma source will be a 270 kW plasma source, utilizing all available power produced by 4 individual power supplies. In addition a pulsed plasma source is being developed to simulate transient heat loads with a duration of 0.5-1 ms as they occur during so-called ELM instabilities [4] in the tokamak. A target value of 2 GW/m^2 for 0.5 ms is planned [5]. For this transient operation a capacitor bank (8400 μF) is connected parallel to the steady-state power supplies.

To achieve the electron temperatures of 10 eV radio-frequency heating is foreseen. The RF power level currently considered is approximately 50 kW. Two RF heating methods are proposed: lower hybrid (LH) heating and ion cyclotron resonance (ICR) heating [6, 7]. Both methods are studied and are being tested on PILOT-PSI.

The target system consists of the user-defined target head, the target manipulator and the target exchange chamber (see figure 1). The target head is attached to the target manipulator allowing the withdrawal of the target from its exposure position to the target exchange chamber (see figure 1). This target exchange chamber can be isolated from the main vacuum chamber with its exposure chamber via a double gate valve system. This allows for an in-situ transfer of the target from the exposure location to the target exchange chamber in less than 30 seconds in the presence of the magnetic field.

Magnum-PSI will start operation in the middle of 2011.

2.2. PILOT-PSI

Pilot-PSI is the forerunner experiment of Magnum-PSI mainly as test-bed for plasma source development and RF heating development. Pilot-PSI has copper coils able to produce a linear magnetic field of 1.6 T in pulsed operation of up to 10 s. In contrast to Magnum-PSI the target is perpendicular to the magnetic field.

High ion fluxes in excess of 10^{25} $m^{-2}s^{-1}$ have already been achieved on Pilot-PSI [8]. At very low gas flows the plasma density can be reduced to $n_e \sim 10^{19}$ m^{-3}. This is consistent with the electron densities in front of the main chamber wall components of ITER. In general the ion energies can always be increased by biasing. Taking this into account the ion fluxes in Pilot-PSI at low electron densities are consistent with the ion fluxes to the main chamber components of ITER as well.

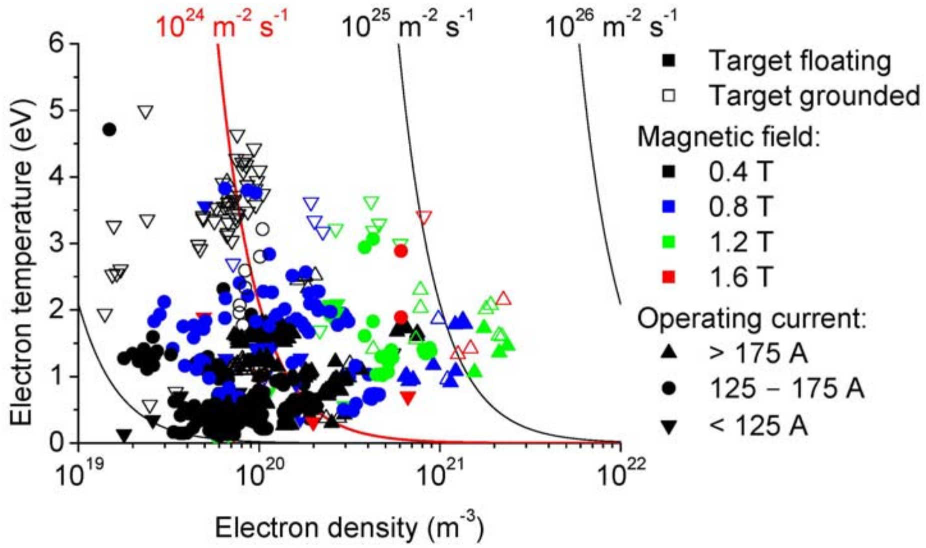

Fig. 2 – Pilot-PSI. Operational domain with floating target and grounded target.

Table 1

Specifications and achievements of the linear plasma wall interaction simulators Magnum-PSI and Pilot-PSI. The ion flux density at the target is given for normal incidence target inclination. With ITER-like grazing incidence the ion flux density is decreased by roughly a factor 10.

	Magnum specifications	**Pilot achieved**	**Pulsed plasma source**
Power [kW]	270	45	3500
Pressure source [Pa]	10^4	10^4	
Pressure target [Pa]	< 3	1-10	
Ti target [eV]	0.1-10	0.1-5	
Te target [eV]	0.1-10	0.1-5	~ 10
n_i target [m^{-3}]	10^{19}-10^{21}	10^{19}-10^{21}	~ 2 x 10^{22}
Ion flux target [m^{-2} s^{-1}]	10^{23}-10^{25}	10^{23}-10^{25}	
Power flux target [MW m^{-2}]	10	30	2000
B [T]	3	1.6	1.6
Beam diameter [cm]	10-1.5	1.5	2.0
Pulse length [s]	steady state	10	0.0005
Extra heating [kW]	50	0	0
Target size [cm]	60 x 12	2.5	2.5

In summary the devices Magnum-PSI and Pilot-PSI are able to simulate both, the ITER divertor conditions as well as the ITER main chamber conditions with the caveat that the electron temperatures close to the main chamber plasma facing components (up to 70 eV) cannot be re-created in those devices.

3. RESEARCH PROGRAMME

Plasma-facing material research for ITER and fusion reactors beyond ITER will be carried out mainly on Magnum-PSI, in parallel with numerical modeling studies. Through the modeling, the link to PSI experiments in tokamaks is made, where circumstances are more complex (geometry, the scrape-off-layer) and diagnostic access is worse. The focus in these studies is on carbon based materials and refractory metals. First experiments are being carried out already on Pilot-PSI. The high plasma fluxes already achieved on Pilot-PSI have been exploited to perform unique ITER-relevant experiments on the chemical erosion of carbon. Research into carbon-based materials has been focused on chemical erosion by hydrogen plasmas. Results from plasma exposure to high-flux (> 10^{23} $m^{-2}s^{-2}$) and low electron temperature hydrogen plasma indicate silicon carbide has a lower relative rate of gross erosion than other carbon-based materials (*e.g.* graphite, diamond, carbon-fiber composites) by about a factor of 10 [9].

Hydrogen retention in refractory metals like Mo and W has been studied extensively in Pilot-PSI. It appears that the hydrogen retention is mainly a function of the plasma facing material temperature, making those metals attractive plasma facing materials for future fusion reactors like DEMO, which have a higher wall temperature. However, neutron irradiation of materials might alter the hydrogen retention in those metals. To study this effect tungsten targets were exposed to high energy tungsten ion beams to simulate the displacement of lattice atoms. The damage induced by irradiation of W targets with 12.3 MeV W4+ ions has been found to enhance hydrogenic retention by a factor of up to 20 [10]. Across the damage levels examined in this study (0.5 dpa – 10 dpa) there was no change in retention, indicating a saturation of the enhancement of retention at levels > 0.5 dpa. Plasma facing materials in future fusion reactors will also experience high thermal stresses both from steady-state heat loads (< 10 MW/m^2) and transient events like ELMs (< 1 GW/m^2). These thermal stresses can lead to extensive cracking of the surface. This surface damage might have an impact on the hydrogen retention in refractory metals. To investigate this effect, W targets were exposed to high thermal heat loads in the JUDITH e-beam facility, which resulted in cracking of the surface. The targets with surface cracking were then exposed to high flux deuterium plasma in Pilot-PSI. The thermally stressed W was found to have increased hydrogen retention of a factor of 2 [11]. However, no difference between moderate and extensive cracking was found. In the future the targets will be exposed simultaneously to the high flux steady-state plasma and the transient plasma fluxes.

4. SUMMARY

Magnum-PSI will give unique contributions to Plasma-facing materials research for fusion reactors:

- ITER divertor flux densities in steady state at ITER relevant electron temperatures (flux densities are a factor of 100 higher than any other device)
- Synergetic effects of high flux densities and radiation damage
- Transient heat loads with high ion fluxes to simulate ELMs
- Exposure of complete vertical target mock-ups with magnetic field line angles to the target similar to ITER
- In-situ analysis of large scale (ITER-like) targets
- Simulation of radiation damage in large scale (ITER-like) targets
- Confinement of small dust particles (in tens of nm-scale range).

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